# SOLID STATE HIGH POWER PULSE SWITCHING

by

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## ABSTRACT

In this paper, the structural features and the methods of turning on high power thyristors, reverse blocking diode thyristors and light activated silicon switches are reviewed. The advantages and limitations of these devices are described together with a description of the performance achieved to date by the various devices. Finally, the operation of these devices in series strings to form high power switching modules is described.

## Introduction

Fifteen years ago, the highest rating of a semiconductor switch was 80 amperes and 1400 volts, and since that time, there has been a steady growth in the power than can be switched. Today, solid state devices capable of switching megawatts of power are commonplace. The highest blocking voltage of these devices has now reached about 5kV, but due to fundamental limitations, significant further improvement is unlikely. Current handling capability on the other hand is likely to grow steadily as devices with ever increasingly larger conducting area are being developed. These devices are operated at an average current density of about $100A/cm^2$ at the present time, and devices with over thirty square centimeters of conduction are available. As the crystal growth techniques are developed and other process improvements are made, we can look forward to even higher current ratings. Devices with over forty square centimeters of conducting area are now under development.

All of these switches have been designed for high duty cycle operation at low frequency. The switching speed of these devices is relatively slow although some devices employing special electrode structures and processing techniques have been designed to operate at frequencies up to tens of kilohertz. However, the inherent switching speed of thyristor type structures is relatively slow when conventional triggering techniques are employed. There have been some recent developments that have dramatically increased the switch-on speed of high power thyristor type devices. By operating these devices at a low duty cycle, it seems possible that nanosecond switching times and conduction of tens of thousands of amperes are feasible. Such extremely high rates of rise and peak current levels of power switching have only been possible

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up to the present time by using spark-gaps. These devices suffer from problems of reliability and short operating life, and are confined to very low switching frequencies. The firing techniques and structures described in this paper lead us to conclude that solid state devices can achieve the same high level of power switching as spark gaps and, at the same time, exhibit the reliability and longevity associated with semiconductor devices.

The operation of the basic thyristor is first described and some basic limitations are outlined, and this is followed by a description of the amplifying gate structure with increased di/dt rating. The structure of the RBDT*, an even higher di/dt device, will then be discussed. Finally, the highest di/dt semiconductor structure, the light activated silicon switch, will be described.

The use of these devices in switching circuits will be discussed, together with various techniques to fire the arrays of devices.

## Thyristor Operation

When a thyristor is turned on by a pulse of gate trigger current, the rate-of-rise of anode current must be limited by the external circuit. The reason for this is that only a small area of the device is initially turned on and the resultant power dissipation in the "on" or conducting region must be kept down to safe limits. This is best explained by referring to Fig. 1 which shows the cross section of a conventional thyristor. Let us assume that the device is in the off state and the anode contact is at some high positive potential relative to the cathode contact. The central p-n junction is reverse-biased and a depletion region, shown cross-hatched in Fig. 1, exists. The device can be turned on by applying a small positive signal to the gate electrode relative to the cathode. The resultant gate current will flow along the path indicated from the gate to the cathode electrode. If the current is large enough, the voltage drop laterally within the p-base region underneath the $n^+$ emitter will be sufficient to forward bias the p-$n^+$ junction and electrons will be injected into the base region at the inside edge of the cathode. These electrons will diffuse towards the depleted region and then be carried by drift within the depleted region due to the high electric field. Upon reaching the other side of the depleted region, the electrons will forward-bias the anode p-n junction, causing the injection of holes into the n-base region. These holes will traverse the device in a manner similar to the electrons and result in further forward bias of the cathode p-$n^+$ junction. This will result in further electron injection from the cathode and hence further hole injection. The net result will be double injection of charge into the base regions and the voltage across the depletion region will collapse. The turn-on process has now commenced and current flows at the inside edge region of the cathode. This results in anode current flowing in this region as indicated in Fig. 1. This "on" region" will then spread at about forty microns per microsecond until the entire cathode region is conducting. However, the anode current must be limited by the external circuit until the conducting area has grown to such a size that extremely high current densities are not encountered.

When the turn-on process is completed, a plasma of electrons and holes exists in the base regions of the device with a density of about $10^{18}$ cm$^{-3}$.

The conducting region in a thyristor can be observed by imaging the infrared radiation emitted from the recombination of electrons and holes

*Formerly known as the RSR.

within the on region in the device. This is done by etching an array of small holes in the cathode electrode to allow the radiation to leave the device. The radiation is observed using an image converter tube, and by gating the imaging system, the turn-on process in a thyristor can be examined in detail.

Figure 2 shows the on region in a thyristor 12 μsec after initiation of turn on carrying 140A, 50 μsec after initiation of turn on carrying 350A, and finally 120 μsec after turn on carrying 400A. Note here the small fraction of the total device area that is initially turned on.
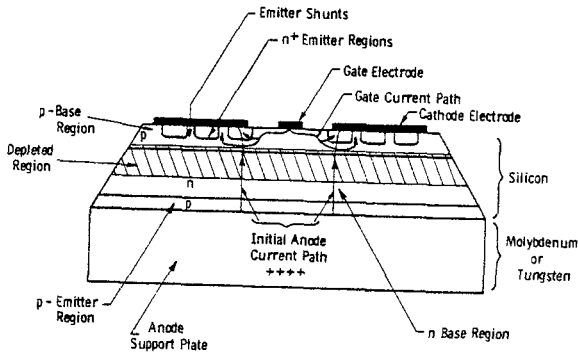


Fig. 1. Cross section of a conventional thyristor (not to scale) illustrating the turn on process.



Fig. 2. Images of the infrared radiation emitted from a conventional thyristor taken at various times after the initiation of turn on. This shows how the spreading of the conduction region takes place from the center of the device.

One way of improving the device is to increase the inside perimeter of the cathode electrode so that the initial on region will be larger and hence the current can be allowed to rise more rapidly. However, if this is done the gate current to fire the device will become excessively large because of the lower lateral resistance of the p-base region. This can be compensated by incorporating an amplifying gate. A cross section of a device with this feature is shown in Fig. 3. Here a small thyristor is integrated into the center of the thyristor. This is the $n^+$ emitter region beneath the floating pilot cathode electrode. The turn-on of the device is similar to the first case discussed and a gate current is made to flow from the gate electrode to the cathode (labeled 1). The geometry of the n emitter regions is adjusted so that the emitter beneath the floating cathode becomes forward biased before the main emitter region. The gate current then causes injection from the pilot cathode and this area turns on and results in pilot cathode current (labeled 2). This current then supplements the original gate current and assists in turning on the main cathode region, resulting in the flow of main cathode current (labeled 3). The floating pilot cathode electrode and the main cathode can be designed with an interdigitated pattern, giving the desired large cathode perimeter. The current can be allowed to rise fairly rapidly in such devices, typically at the rate of about 2000A/μsec. An interdigitated amplifying gate thyristor is shown in Fig. 4.
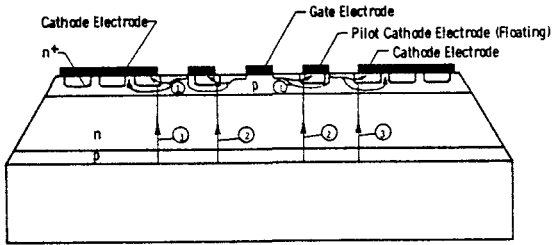
Fig. 3.  Cross section of a thyristor in-
corporating an amplifying gate
structure.  Here the sequence of
turn on is illustrated, starting
with a gate current labeled 1,
resulting in a pilot anode
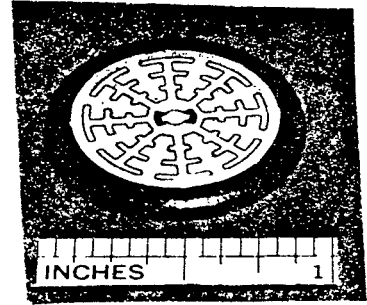current 2 which in turn results
in a main anode current 3.



Fig. 4.  A thyristor chip in-
corporating an amplifyin
gate and interdigitated
cathode electrode.

### Reverse Blocking Diode Thyristor (RBDT)

This two terminal structure is shown in cross section in Fig. 5.  The
device is switched on by applying a positive pulse to the anode electrode.
An explanation of the device operation is as follows:  Let the anode
electrode be at a high positive potential.  Most of the n and p base will
be depleted of charge because the voltage is dropped across the reverse
biased center p-n junction.  In this state the device can be regarded as
a capacitor.  If now a positive voltage pulse is applied to the anode,
charge will flow within the device to further charge the capacitor.  This
current will flow in the manner indicated in Fig. 5 beneath each of the n
emitter regions and hence to the cathode electrode via the emitter shunts.
If this capacitive current is large enough, it will create a lateral voltage
drop sufficient to forward bias the emitter p-n junctions.  The emitter
regions will become forward biased at a large number of points in the
emitter pattern.  In this manner, a large area of the device can be turned
on rapidly.  These devices are well suited for series stacking because it
is not necessary to produce the isolated trigger circuitry that is required
for conventional thyristor stacks.

Devices of this type have demonstrated rates of rise of current up to
8000A/μsec, and are commercially available in two sizes.*

### Light Activated Semiconductor Switch

The fastest turn on is achieved by the light activated silicon switch
(LASS) which is shown schematically in Fig. 6.  This again is a two-terminal
pnpn structure.  If a positive potential is applied to the anode electrode,
the center p-n junction will be reverse biased and carriers will be depleted

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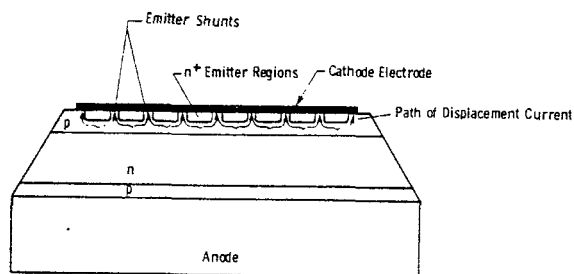
*Westinghouse types T40R and T60R.

Fig. 5. Cross section of a reverse conducting thyristor showing the displacement current paths when the anode is subjected to a positive step of voltage. This current causes the emitter junctions to become forward biased and turn on takes place over a large area of the device.
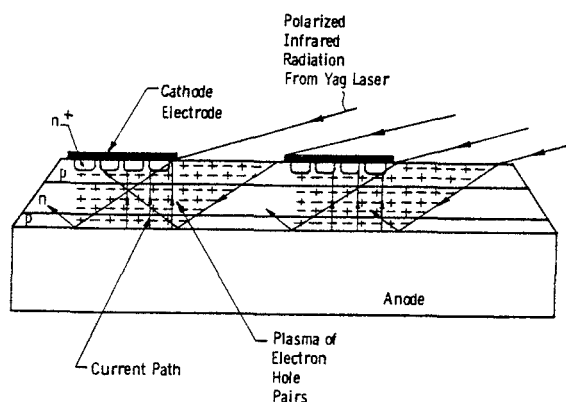


Fig. 6. Schematic cross section of a light activated semiconductor switch.

from the central region and the device will be in the forward blocking (off) state. In all the devices described earlier, turn on involved various means of obtaining injection of electrons and holes from the cathode and anode to achieve a high injected plasma charge density. This is a relatively slow mechanism because it involves diffusion processes which are inherently slow. There is another, much faster, method of creating a plasma of electrons and holes in the base regions and that is by optical absorption. By illuminating the silicon with light, photons can be absorbed and create electron-hole pairs. This process is extremely rapid and can take place within the depletion region, creating a plasma without having to rely on diffusion of charge from the electrode regions.

In practice, the infrared radiation is obtained from a neodymium doped YAG laser and has a wavelength of 1.06 microns. Such radiation is closely matched to the band gap of silicon and results in efficient conversion of photons to electron hole pairs. To obtain more efficient optical coupling to the silicon, the polarized radiation is introduced into the silicon at the Brewster angle.

Using this technique, the plasma of electrons and holes that normally exist in the base regions of a thyristor in conduction can be instantaneously produced. The area of turn on can be large and transit time limitations associated with establishment of the plasma by injection from the cathode and anode emitters are greatly reduced. Furthermore, series stacking is greatly simplified by the isolated nature of the trigger system.

A stack of ten devices fired with a single laser using a beam splitter system has been operated at 4000A/µsec with a peak current of 1800 amperes at a 60 Hz repetition rate. The power limit was set by the circuit and not by the devices. Each thyristor was capable of blocking 1200 volts.

A test apparatus designed to produce fast rising current pulses is shown schematically in Fig. 7. This apparatus is composed of 40 pulse

forming networks (PFN's) arranged in parallel to give an effective characteristic impedance of 0.04Ω, the electrical length of the pulse forming network being 40 μsec. The circuit is designed to be charged to 2000 volts. A 50 mm diameter light fired semiconductor switch is located at the center of the pulse forming networks and is used to switch the power from the PFN's into the load resistors. The laser on the left of Fig. 7 is directed at the multifurcated light pipe, which in turn is directed through the specially designed window in the silicon switch. Using this technique we have switched peak currents of 25KA at rates up to 40KA/μsec. The waveform of such a switching event is shown in Fig. 8.
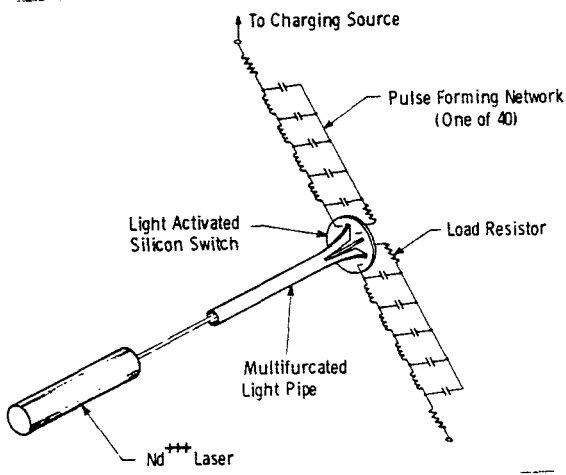


Fig. 7.  Schematic of light activated silicon switch test apparatus. When the laser turns on the silicon switch, the energy stored in the pulse forming networks is discharged through the switch into the load resistors.
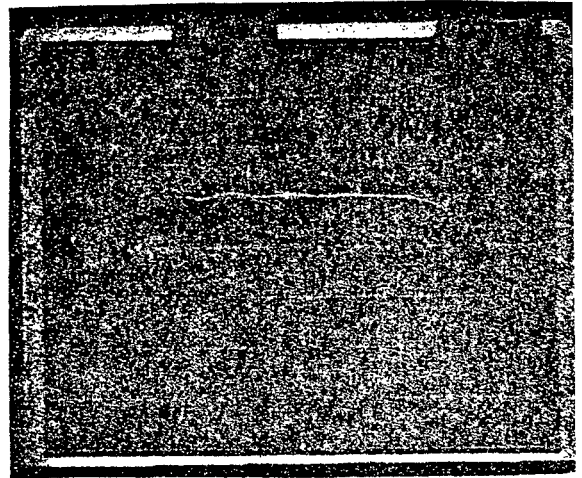
Fig. 8.  Current waveform obtained by discharging system in Fig. 7. The time scale is 5 μsec/division, current scale 5KA/division.

Even higher rates[1] of current rise have been achieved using parallel connected strip lines and low inductance connections. In this case, peak currents of 10KA and current rates of rise of 750KA/μsec have been measured. Pulse lengths in this case were 100 nsec. The results are summarized in Table

### Table 1

| Line Impedance (Ω) | Charge Voltage (V) | Peak Current (A) | Pulse Length | $\frac{di}{dt}$ (KA/μsec) | Peak Power (MW) |
|---|---|---|---|---|---|
| 50 | 750 | 16 | 100 nsec | 3.75 | 0.011 |
| 0.104 | 1020 | 9820 | 100 nsec | 755 | 10.0 |
| 0.040 | 1700 | 25000 | 40 μsec | 40 | 42.5 |

Circuit Considerations

Pulse network charging voltages in the multikilovolt range are common-place in radar modulation circuits, while the most advanced short pulse applications call for switches which can block from 100 kV to 1 MV. Since the basic devices used for switch construction are limited to a few kilo-volts, the need for series operation of semiconductor switching devices is obvious.

The modularity of power pulse switching circuitry utilizing semi-conductor devices can be of great benefit to the circuit designer because it provides an additional degree of flexibility not otherwise available. A given set of load requirements can be satisfied using a single series string of switching devices, or by combinations of series-connected devices switching individual pulse networks whose outputs are combined and coupled to the load by a pulse transformer. Although this flexibility is not available across the board, it does offer a valuable option within certain limits.

Although series connection of switching devices is feasible and attractive, direct paralleling is generally avoided. Unless passive current sharing components are placed in series with parallel connected devices, current is generally not shared equally defeating the purpose of the parallel connection. The use of passive current sharing components is expensive and results in the introduction of undesirable series voltage drops. Therefore, direct paralleling of switching devices is not considered in subsequent discussions. If, however, current multiplication is needed, individual switches can be used to discharge individual networks into a common load or into a pulse transformer primary.

The types of solid state switches discussed will then be arrays of semiconductor switching devices connected in series to obtain a relatively high voltage blocking capability.

## Series Operation Considerations

When a number of switching devices are series-connected to hold off a high PFN charge voltage, a resistor must be connected in parallel with each device to insure uniform division of the PFN voltage between all switching devices when in the off state as shown in Fig. 9. All resistors, $R_{a1}$ to $R_{an}$, should be equal in value and should be low enough in resistance to swamp out differences in switching device leakage currents over the full range of operating temperatures, but they should be high enough so that the PFN is not discharged appreciably between pulses.

A four layer switching device can be triggered on by a sharply rising voltage transient appearing between anode and cathode. To guard against such an occurrence at an undesirable time caused by a miscellaneous circuit transient, RC networks are sometimes connected across each of the switching devices in the series string as shown also in Fig. 9 as $R_{b1}$ to $R_{bn}$ and $C_1$ to $C_n$.

The complexity of the triggering apparatus required depends upon the type of basic device structure used in the switch. The purpose of the triggering circuitry is to turn on at the same instant all individual switching devices which comprise the complete switch. In practice, however, this is impossible to accomplish because all switching devices do not exhibit the same delay time, defined as the interval between receipt of the triggering stimulus and the time when anode voltage begins to fall. The effects of delay time on switch performance are discussed in the following paragraphs.

When a series string of switching devices receives a triggering signal, the devices with shorter turn-on delay times turn on before those whose delay times are longer. When this occurs, the off state voltages formerly blocked by the devices turning on first are shared as increased off state voltages applied to those devices which turn on last. The result of this effect is different for each of the three types of device structures considered, so each one will be discussed in turn.

In a thyristor switch, the result of differences in turn-on delay times between individual devices can be catastrophic failure. If the applied off-state voltages of the devices having longer delay times exceed the maximum forward blocking capability of the device structure before turn-on takes place, catastrophic failure will occur. The presence of the RC snubber network helps to protect against this situation to some extent, but in high power pulse circuitry, the amount of protection the snubber can offer is minimal if other problems are to be avoided. Greater protection is afforded by use of larger values of capacitance, but too large a capacitor increases the turn-on dissipation of the switching device excessivel

The RBDT series string is triggered on by application of a fast-rising, high voltage pulse to all or part of the series string of devices. Devices with short delay times turn on first allowing the triggering voltage they formerly blocked to be applied to the devices with longer delay times. The slower devices then receive added turn-on drive which tends to shorten their remaining turn-on delay time. Because the RBDT turns on as a result of a fast rising high voltage pulse, turn-on delay time phenomena cannot cause catastrophic failure as is the case with the thyristor. If anything, the effects of differing turn-on delay times are minimized by the turn-on mechanism of the RBDT.

The effects on series switch performance of turn-on delay time differences between devices is theoretically the same for the LASS as it is for the thyristor. However, as a consequence of the laser drive used to initiate triggering, turn-on delay time is reduced to a value so small that for all practical purposes it can be ignored. All LASS devices in a series string respond so quickly and uniformly to the laser drive that no voltage increase is observed on any device in the string prior to turn-on.

Circuits which generate high power pulse currents by the discharge of pulse networks in general tend to reverse bias the switching device at the end of the pulse owing to reverse charging of the network. In contrast to the action of a thyratron, a semiconductor switching device will not block reverse voltage immediately following forward pulse current conduction until a reverse current has flowed for a time sufficient to sweep out all stored charge. When this point is reached, reverse current is suddenly interrupted and the device blocks whatever reverse voltage the external circuit impresses on it.

The quantity of stored charge contained in a semiconductor device following forward pulse current conduction varies from device to device. If a switch comprises a series string of semiconductor switching devices, the reverse sweep-out current will be the same for all, but due to stored charge variations, the time duration of reverse current flow before reverse blocking capability is regained will vary from device to device. The device with the smallest amount of stored charge will recover first and then attempt to block the entire voltage impressed upon it by the external circuit. In general, such a condition leads to catastrophic failure in a series switching circuit unless precautions are taken.

For all three device structures considered, turn-off time is minimized when a small amount of reverse bias is applied to the semiconductor switching devices following the end of forward pulse current flow. This can be accomplished by the same circuit techniques used to protect devices against catastrophic reverse voltage transients as shown in Fig. 9. Diode $D_R$ and the resistor $R_R$ serve as a damping network to limit peak reverse voltage applied to the switch overall, as is commonly done in thyratron circuits. Individual stored charge variations between semiconductor switching devices are taken into account by the placement of individual diodes, $D_1$ to $D_n$, in antiparallel connection across each switching device. When the device containing the smallest quantity of stored charge recovers, the reverse switch current interrupted by it is diverted to its antiparallel diode which provides a path for it to flow and prevents the generation of a high reverse voltage transient.

In general, semiconductor switching devices tailored for optimum pulse switching do not also exhibit short turn-off time. At present, RBDT devices are manufactured with turn-off times in the range of 100 to 200 µs at rated junction temperature, and although thyristors can be made with turn-off times much less than these, the thyristors suitable for fast pulse switching have turn-off times between 100 and 200 µs as well. The situation regarding the turn-off time of the LASS is less clear because LASS has not yet been fully evaluated in pulse circuitry. Present LASS devices are made from thyristor structures with turn-off times ranging from 50 to 100 µs, but it appears that, in the future, devices with shorter values of turn-off time can be developed.

## Comparison of Alternatives

Each of the switching device structures considered offers a certain combination of performance parameters. When a device must be chosen for a given application, the best fit between the requirements of the application and device performance should be obtained.

From the standpoint of voltage blocking capability, there is little to choose from at present between the thyristor, the RBDT, and the LASS. The basic fast switching structures of all three are capable of blocking about the same voltage. In virtually all cases, individual devices must be series-connected to realize a high voltage switch.

For short pulse work (less than 20 µs), the maximum allowable peak current is related to di/dt, pulse length, and PRF. The thyristor structure is the poorest, in regard to the compromise. The RBDT is next, and the best is the LASS because its turn-on losses are lower.

The maximum allowable di/dt is dependent on peak current, pulse length, and PRF. The larger the initial area turned on, the higher the maximum allowable value of di/dt as discussed earlier. In this regard, the thyristor is the poorest, the RBDT is better, and the LASS the best.

Semiconductor device turn-off time depends upon the combination of parameters chosen for device design, and in addition, it depends on junction temperature. If a hot spot is developed at a given point on the surface of the device owing to small area turn-on, it will be the determining factor for turn-off time. In regard to turn-off time, then, the RBDT is superior to the thyristor. Because it has not yet been fully evaluated, the turn-off time of the LASS operating in fast, high power pulse circuitry has yet to be determined.

Each of the three device structures considered requires a different form of trigger. The simplest to trigger is the thyristor which requires

a relatively small gate current of the order of a few amperes at several
volts. In series string connections, however, the current for each device
must be supplied by an isolated source. The RBDT requires a high voltage,
fast rising voltage pulse of sufficient amplitude to break over all or a
substantial part of the series string of devices. The trigger pulse, which
must have a leading edge rate-of-rise between 5 and 10 kV/μs, need not be
more than a few microseconds in duration regardless of load current pulse
length. The LASS must be triggered by radiation of a certain wavelength.
The required pulse is best produced by a neodymium YAG laser. The radiation
can be distributed to the individual devices connected in a series string by
use of fiber optics or with conventional optics using beam splitters.

Triggering techniques increase in complexity and cost in going from
the thyristor to the RBDT to the LASS. When a device is chosen for use
in a given application, the increased system cost resulting from the require-
ment for a more complex triggering system must be justified by the necessity
for the higher di/dt capability obtained.

### Basic Circuit Techniques

For the purposes of this discussion, the switch will be assumed to
serve as the device which discharges a PFN or line into a load matched
reasonably closely to the network or line characteristic impedance. This
type of basic circuit configuration covers generally most applications from
small radar modulators to high power laser pulsers.

Shown in Fig. 10 is a simplified basic configuration of a discharge
circuit using a series thyristor switch. As discussed earlier, shunting
diodes, snubber networks and voltage equalizing components may be included
if called for in the application. Each thyristor must be gated on by an
isolated gating circuit. A common triggering signal must initiate simultaneous
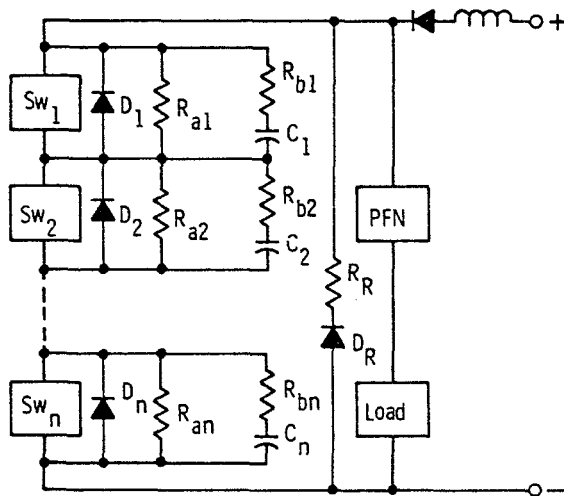gate current injection into all thyristors to minimize turn-on voltage spikes.



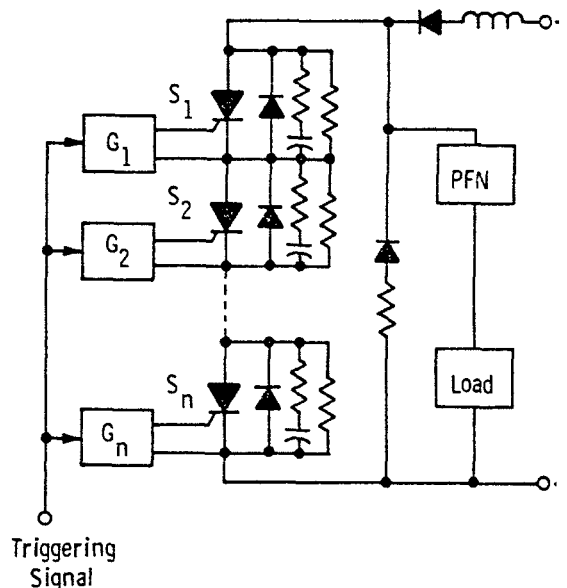Fig. 9. Basic pulse circuit.



Triggering
Signal

Fig. 10. Circuit using thyristor
switch.

Shown in Fig. 11 is a simplified basic configuration of a discharge
circuit using a series RBDT switch. Each RBDT device is shunted by a diode,

a snubber network reduced to a small capacitor only, and a voltage equalizing resistor. A short, fast rising high voltage pulse is delivered to the switch by the secondary of the trigger pulse transformer. Diode $D_1$ prevents the PFN from shorting the trigger pulse to ground, and diode $D_2$ prevents the PFN from discharging through the pulse transformer. Diode $D_3$ helps to further limit peak reverse voltage. The trigger pulse must be generated by the discharge of a capacitor into the primary of the trigger transformer by a fast switch such as another RBDT or a thyratron. The trigger pulse is applied to the entire switch by diode $D_2$. In other configurations, the pulse can be applied to a portion of the series string as long as the portion is greater than 1/2.

   Shown in Fig. 12 is a simplified basic configuration of a discharge circuit using a series LASS switch. The LASS devices are shunted by antiparallel diodes and voltage equalizing resistors. It appears that in some applications, small snubber networks will be required, but because of the negligibly small turn-on delay times, no dynamic equalizing capacitance is needed.
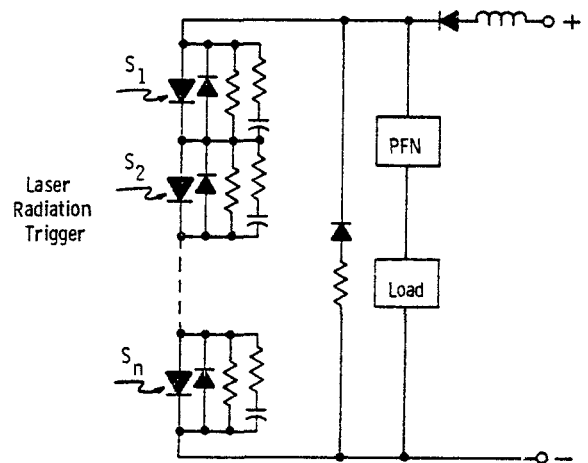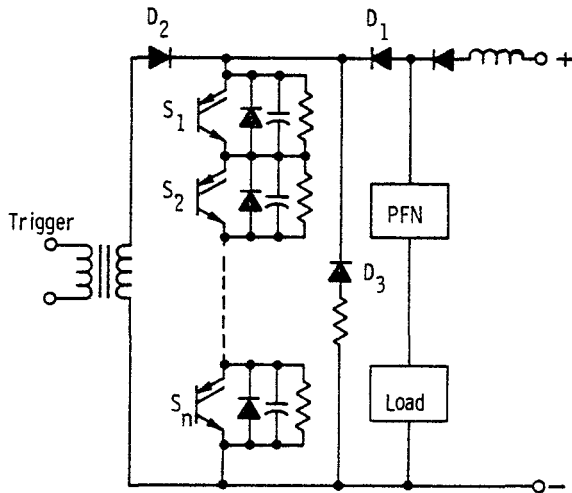


Fig. 11.   Circuit using RBDT switch.     Fig. 12.   Circuit using LASS switch.

   The radiation applied to trigger the LASS devices is provided by a neodymium YAG laser. It can be delivered to the devices in one of two ways. As shown in Fig. 13, conventional optics with beam spitters located near each of the devices can be employed to direct a certain portion of the laser radiation toward each device while passing on an appropriate amount to the remaining devices. On the other hand, fiber optics of the type shown in Fig. 14 can be used.

Conclusions

   As a result of advances made in the semiconductor industry, several solid state pulse power switching devices are now either available or under development. These will make possible pulse generation ranging from negligibly small values of di/dt to levels higher than $10^{12}$ A/sec. As switching devices with increasingly high di/dt ratings are selected for application, the complexity and cost of triggering increases also. It is important, therefore, to select the device best suited to each application,
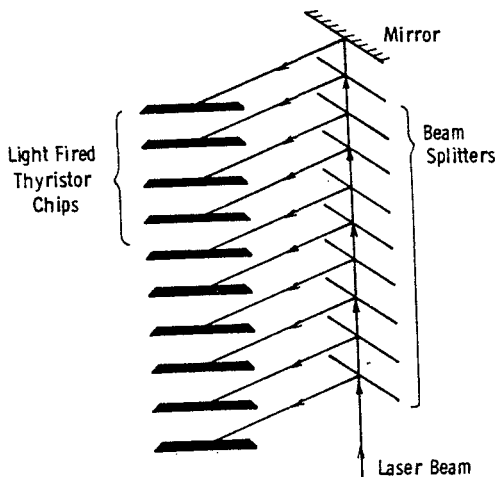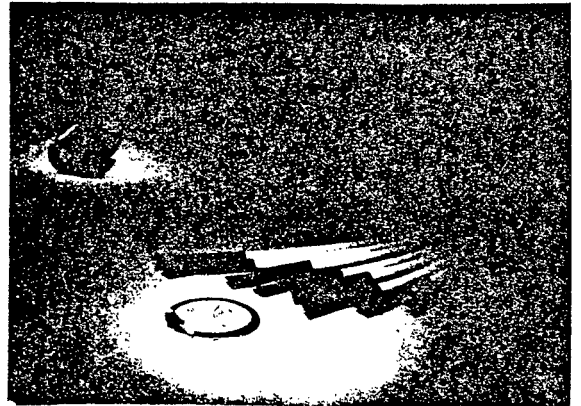
Fig. 13.   Beam splitter optical system.



Fig. 14.   Fiber optic cables.

and to make sure that the device selected is not overly qualified, because
if it is circuit cost will be increased beyond the level where it should be.
Thyristors of many types are available now for limited use in pulse
switching applications.   RBDT devices are available and have been used
in a number of radar modulators.[2]   Devices employing the LASS structure
are now under development supported by government contracts.   Because
the LASS is still under development, it has not been fully characterized
to determine the ultimate limits of its peak current and di/dt capabilities.

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